Waste Management

Electromagnetic Induction Methods Applied to an Abandoned Manure Handling Site to Determine Nutrient Buildup

Roger A. Eigenberg* and John A. Nienaber

ABSTRACT

Movement of nutrients from livestock manure handling sites has the potential to negatively impact the environment. This study was conducted using electromagnetic induction (EMI) measurements to develop apparent soil electrical conductivity (EC_a) maps to identify regions of nutrient buildup beneath an abandoned compost site. A trailer-mounted EM-38 coupled with a global positioning satellite system was towed across an area used for composting of feedlot manure. The resulting EC_a maps were compared with known locations of compost rows confirming the alignment of row locations with high EC_a regions. The identified rows were cored and compared with the region between the rows. The identified rows with a compost history demonstrated significant ($P < 0.05$) increases in soluble salts (1.6 times greater), NO_3 (6.0 times greater), and Cl (2.0 times greater) compared with the area between the rows at a 1.5-m depth. Image processing techniques were used to display yearly changes that were associated with nutrient movement and transformations in the soil beneath the site. Correlations between EMI measurements and soil core analyses for NO_3–N, Cl, and EC provided ancillary support for the EMI methods. The use of EMI for mapping of sites having a history of livestock waste application was effective in delineating high nutrient buildup areas and for observing spatial EC_a changes over time.

MONITORING OF NUTRIENT BUILDUP in soils at manure handling and application sites is necessary to assess risk potential. Coring provides precision in both composition and position, but comes at an expense in time and resources and it may not account for spatial variability that can occur at manure management and handling sites. Alternative methods are needed to evaluate the relative level of possible contaminants beneath the surface. Geophysical tools, such as electromagnetic induction soil conductivity instruments, have the potential to offer spatial and temporal components for delineating regions of high nutrient buildup.

Commercial instruments are available that use electromagnetic induction (EMI) methods to provide a noninvasive method of measuring soil electrical conductivity. For near-surface EMI measurements, the instruments contain both a transmitter and receiver, with the associated coils usually at a fixed (1–4 m) separation. The signal sent out from the transmitter interacts with the soil and causes a secondary electromagnetic field that is detected by the receiver. The relative strength of the secondary electromagnetic field, with respect to the primary field, provides an estimate of the apparent soil electrical conductivity, EC_a.

Electromagnetic induction techniques are applicable for mapping EC_a to depths useful for the agriculturalist (McNeill, 1990). Apparent electrical soil conductivity measurements using EMI have been shown to be useful in locating seepage from animal waste lagoons (Ranjan et al., 1995). Sudduth and Kitchen (1993) used EMI methods to estimate clay pan depth in soil. Soil salinity hazards have been mapped using EMI methods (Williams and Baker, 1982; Corwin and Rhoades, 1982). Eigenberg et al. (2001) found EC_a to be a reliable indicator of NO_3–N gains and losses in soil at a research cornfield site. Similarly, electrical conductivity (EC, 1:1 soil to water mixture) was shown to be a measure of soluble nutrients (Smith and Doran, 1996) and Doran et al. (1996) demonstrated the predictive capability of EC to estimate soil NO_3–N.

The EC of a solution is related to the ionic concentration (either cations or anions) in the solution. Beef cattle manure contains N, P, K, Ca, Mg, S, Na, Cl, Fe, and other trace elements. Electrical conductivity of beef cattle manure as removed from a feedlot is highly variable but on average is approximately 37.0 dS m^{-1} (Gilbertson et al., 1975). Average soil may have an EC of near zero to 11.4 dS m^{-1}, depending on texture and salinity (Smith and Doran, 1996). The use of beef cattle manure as a soil amendment has the potential of increasing EC. Electrical conductivity methods have been shown to be sensitive to areas of high nutrient levels (Eigenberg et al., 1998) and have been used to detect ionic concentrations on or near the soil surface, resulting from field application of cattle feedlot manure.

The purpose of this work was to test the use of EMI for locating compost rows associated with an abandoned composting operation. Soil cores were taken to validate row locations, as well as to establish depth of movement of nutrients associated with the composting process. Furthermore, electromagnetic maps of the former waste management site were generated annually. This "time lapse" sequence was planned to allow observation of temporal effects of nutrient movement or transformation within the soil profile. Soil core data were then used to help explain observed map changes in EC_a values.

MATERIALS AND METHODS

Compost Site

Nonirrigated acreage between pivots located at the U.S. Meat Animal Research Center (USMARC) was used for com-

USDA Agricultural Research Service, U.S. Meat Animal Research Center, Biological Engineering Research Unit, P.O. Box 166, Clay Center, NE 68933. Received 21 Jan. 2002. *Corresponding author (eigenberg@email.marc.usda.gov).

Abbreviations: EC, soil electrical conductivity; EC_a, apparent soil electrical conductivity; EMI, electromagnetic induction; GPS, global positioning system.

posting of feedlot manure for four consecutive seasons (1991–1994). The soil at this site belongs to the taxonomic class of fine, montmorillonitic, mesic Pachic Argiustolls and has 1% or less slope. Compost windrows were maintained in a well-defined north–south orientation with windrow locations remaining stable through the period. The site was maintained with a mowed vegetative cover from 1995 through 1999. No fertilizer or other amendments were applied to this site from 1995 through 1999.

Survey Equipment

A commercial EMI soil electrical conductivity meter (EM-38; Geonics Ltd., Mississauga, ON, Canada[1]) was used in this study. The EM-38 incorporates the transmitter and receiver coils fixed within the instrument with an intercoil spacing of 1.0 m. The instrument's output is the apparent bulk electrical conductivity, EC_a, in dS m^{-1}. The instrument was calibrated before each survey according to the manufacturer's established procedure. For the data collected in this study, the EM-38 was operated in both the horizontal and vertical mode, having a response that varies with depth in the soil. With the EM-38 operated at ground level the effective exploration depth is near 0.75 m for horizontal dipole and 1.5 m for vertical dipole mode (McNeill, 1990). Electromagnetic induction readings were taken at coring sites with the EM-38 instrument on the ground in both horizontal and vertical orientations. Mapping was accomplished with the EM-38 mounted on a trailer that was pulled behind an all-terrain vehicle (ATV). The trailer was constructed of nonmetalic materials (fiberglass, plastic, wood, and rubber), with the exception of metal in the axles of the wheels. The trailer elevated the EM-38 to 42 cm above the soil surface on smooth soil, with the data corrected to ground level for comparable readings (Eigenberg et al. 2000).

A Trimble PRO-XL global positioning system (GPS; Trimble Navigation, Sunnyvale, CA) with differential correction (sub-meter accuracy) was used to obtain positional data in UTMs (Universal Transverse Mercator coordinates). The EM-38 was connected to the GPS unit (acting as the data collection device) through a small dedicated battery-powered microcomputer (Model IVa; Onset Computer, Pocasset, MA). The computer provided the necessary analog to digital conversion and data formatting to the National Marine Electronics Association (NMEA) serial interface standard. The serial data were sent to the GPS to log positional and EMI readings every second, a rate determined by hardware acquisition capabilities.

Survey Site Selection

An approximate 70- × 70-m portion of this field was surveyed on 1.5-m intervals (Fig. 1) in 1997 using the EM-38 GPS system (images shown in this paper are from the horizontal mode). A smaller section of the compost site was selected (Site I) for additional EMI surveying and for coring. Site I (20 × 20 m) is shown within dashed lines in Fig. 1. This site was chosen based on known, compost row locations (Row B, Fig. 1), and on EMI response for two complete rows and relatively uniform EC_a within the rows. The subsection was set up on a transect of 1.5 m spacing as this interval allowed a distinct track for each pass of the ATV (ATV width is 1.1 m). Given the acquisition rate described above, the speed of the ATV was kept below 1.5 m s^{-1}. The 20- × 20-m subsection
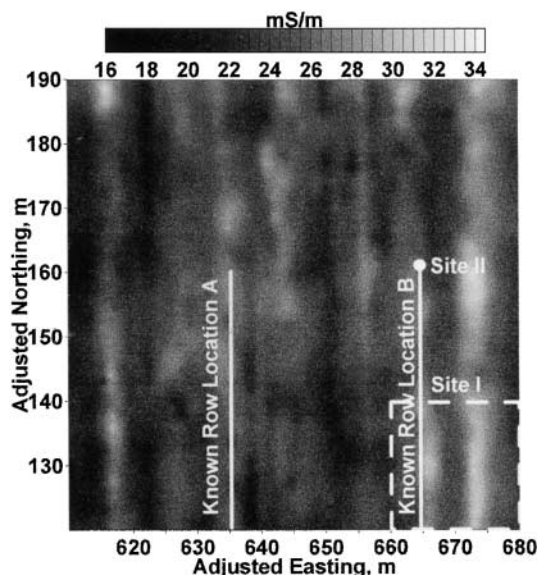

Fig. 1. Electromagnetic survey (apparent soil electrical conductivity [EC_a] map) of an abandoned compost site. The subsection used for detailed study, Site I, including two former compost rows, is shown within the dashed lines. Site II is a coring site, and lines 1 and 2 are former compost row locations based on compost operation records and local landmarks. (Adjusted northing = northing − 4 487 000; adjusted easting = easting − 570 000)

was surveyed at this rate. Surveys were conducted during the fall in 1997, 1998, and 1999.

Site I

The 20- × 20-m subsection of the former compost site was marked for soil coring as shown in Fig. 2. Coring locations were based on the known compost row location (Row B, Fig. 2); the remainder of the coring grid was determined based on known separation between the former compost rows. Rows B and D are on former rows, and Rows A, C, and E are between rows (Fig. 2). Soil cores were taken in October 1997 to a depth of 7.6 m using a Giddings (Fort Collins, CO) hydraulic probe. The cores were analyzed by a commercial lab for constituents associated with feedlot manure including NO_3–N, Cl, SO_3, K, P, NH_4, pH, EC, and moisture. Nitrate nitrogen was sampled at 0.3-m intervals and SO_3, K, P, NH_4, pH, EC, and moisture were determined at 0.3-m intervals to 1.5 m, and then on 1.5-m intervals to 7.6 m.

Site I Electromagnetic Induction Readings

Electromagnetic induction readings were taken (October 1997) at each coring location of Site I (Fig. 2) before probing the soil. The EM-38 was placed on the soil with the instrument oriented in the north–south direction (parallel to the former compost rows) and read in both the horizontal and vertical dipole mode.

Site II

Soil cores were taken at a second coring location, Site II, situated about 36 m due north of Site I (Fig. 1). Site II was accurately located based on compost operation records and local landmarks to be a known center of a former compost row. Soil cores were taken every three years starting in 1993 and were taken with a Giddings hydraulic probe to a depth of 6.1 m at 0.3-m increments for determination of NO_3–N and Cl.
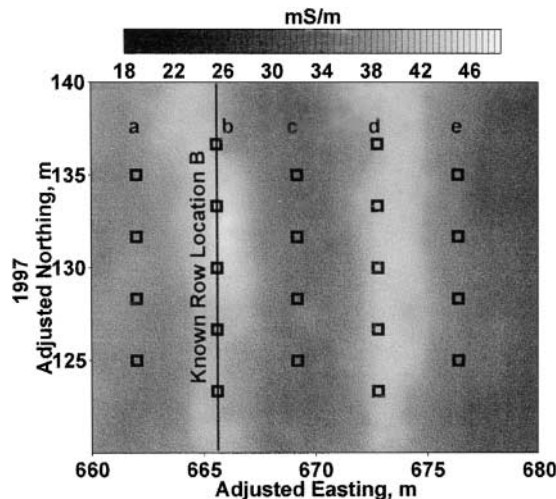
Fig. 2. The layout of a 20- × 20-m subsection (Site I) of the former compost area. The 1997 apparent soil electrical conductivity (EC$_a$) map is shown overlaid on the coring grid. Coring Rows B and D are based on known row locations; A, C, and E are located between the rows. (Adjusted northing = northing − 4 487 000; adjusted easting = easting − 570 000)

Data Handling and Processing

Soil Electrical Conductivity Data

Electromagnetic induction data were transferred to a computer after each survey, with the stored files converted to ASCII format suitable for input into a contouring and three-dimensional mapping program (Surfer; Golden Software, 1995). The EC$_a$ maps were generated using kriging as the geostatistical interpolation method, as the maps were used only for visual interpretation and kriging gives visually appealing plots. The Surfer default values were used for the map images. The grid files were generated by Surfer, and established on a 50 × 50 grid; for the field under study (20 × 20 m) the grid spacing produced a 0.4-m grid resolution in the X and Y direction. This grid resolution was chosen to provide sufficient horizontal and vertical detail for image processing.

Surfer provides a grid math command to mathematically combine grid node values from two grid files that use the same X and Y grid dimensions. This command creates an output grid file based on a defined mathematical function of the form:

$$C = \mathrm{f}(A,B)$$

where C is the output grid file and A and B represent the input grid files.

The first image (1997) in the mapping sequence was used as the base map, M_b, for the subsequent fields. Each subsequent map, M_s, had the base map removed so that:

$$M_d = M_s - M_b$$

where M_d is the difference map.

The remainder in the M_d grid map was the change in EC$_a$ from the time of the base map, M_b, to the time of the subsequent map, M_s.

Soil Core Data

Soil core constituent data means from Site I were compared using a factorial model to test the effect of location (on-row versus between-row) and depth on constituent concentration (PROC GLM; SAS Institute, 1986). PROC GLM was run with a LSMEANS statement and the PDIFF option generating probability values to test mean values of location by depth. Correlations were obtained using PROC CORR (SAS Institute, 1986) for EMI measurements of both instrument orientations (horizontal and vertical) to test for a possible joint property of the EMI measurements and core sample data. The procedure generated a Pearson product–moment correlation with corresponding significance probability.

RESULTS AND DISCUSSION

Apparent Electrical Conductivity Maps

By 1997 the field that had been used for the compost operation had no visible surface features to indicate locations of the former compost site. Apparent soil electrical conductivity was measured in 1997 by EMI (Fig. 1) with values ranging from approximately 0.15 to 0.35 dS m^{-1}. Higher EC$_a$ values are shown as light regions with dark regions indicating low electrical conductivities. The entire region showed a streaked appearance (north to south) that was believed to be associated with former compost rows. During the composting operation (1991 through 1994) two reference compost rows were located by surveying methods based on fixed landmarks at the field site, providing accurate row center locations. The locations associated with the two reference compost rows (Rows A and B, Fig. 1) were marked on the EC$_a$ map. The pattern of relatively high EC$_a$ rows identified on the map is consistent with the reference row locations (Fig. 1).

Soil Cores

Site I

Soil cores were taken (Fig. 2) at Site I with Table 1 listing mean values of soil constituents at select depths for cores taken in the high EC$_a$ region (on rows) and in the low EC$_a$ region (between rows). Table 1 indicates those depths that are significantly different for the "on-row" compared with the "between-row" constituents. Figure 3 displays these differences with plots of Cl, NO$_3$–N, and EC. Nitrate and Cl are distinguishable ($P < 0.05$) with the "on-row" concentrations remaining higher than the "between-row" measures from 0.6 through 2.4 m (Fig. 3); this difference is an anticipated result of the movement of these ions into the soil profile beneath the compost row. Differences in EC were significant from 0.6 through 1.5 m, consistent with the NO$_3$–N and Cl measures (Fig. 3). Soil pH was lower under the row (Table 1), suggesting that organic acids from the manure moved into the soil; also, acidification may have occurred as a result of nitrification of NH$_4$ in the top 1.2 m of soil. Below 1.2 m, pedogenic carbonates probably buffered the acids. Row differences were evident for P at only the first 0.3 m (Table 1), with P higher between the row, possibly indicating runoff from the compost pile accumulated between the rows, elevating P concentration. Additionally, more acidic conditions "on row" may have solubilized the phosphate for plant uptake or leaching. Sulfate trended toward higher values under the old compost row (Table 1). The measures of NH$_4$, moisture, and K generally did not show significant dif-

Table 1. Soil properties with standard deviations at selected depths directly below the old compost rows and between the old compost rows.

Property	Location†	n	Depth (m) 0.3	0.6	0.9	1.2	1.5	3.0	4.6	6.1	7.6
NO$_3$–N, mg kg⁻¹	O	10	22.8 ± 6.3	71.6 ± 17.2	102.7 ± 14.7	103.9 ± 19.1	87.8 ± 15.0	26.4 ± 4.9	7.6 ± 1.7	6.2 ± 2.5	0.9 ± 0.1
	B	12	10.2 ± 1.9	6.8 ± 1.3***	9.4 ± 3.1***	15.6 ± 5.4***	14.6 ± 4.4***	11.7 ± 1.8	10.2 ± 4.3	4.8 ± 2.5	1.1 ± 0.2
Cl, mg kg⁻¹	O	10	41.8 ± 10.5	124.7 ± 39.1	190.7 ± 30.1	214.3 ± 35.3	182.1 ± 29.7	52.0 ± 6.0	22.1 ± 6.9	18.5 ± 13.3	1.8 ± 0.2
	B	12	21.0 ± 6.3	30.6 ± 8.1***	87.1 ± 36.4***	120.0 ± 47.8***	89.0 ± 27.5***	36.1 ± 2.8	10.3 ± 2.3	3.2 ± 0.6	2.3 ± 0.3
NH$_4$, mg kg⁻¹	O	10	6.7 ± 0.4	5.3 ± 0.8	4.5 ± 0.6	3.7 ± 0.2	4.5 ± 0.5	5.8 ± 1.0	5.5 ± 0.5	5.1 ± 0.4	4.8 ± 0.6
	B	12	5.9 ± 1.0	6.7 ± 0.6	6.2 ± 0.7	6.6 ± 0.9**	5.8 ± 1.0	5.4 ± 0.7	4.0 ± 0.6	4.2 ± 0.6	4.7 ± 0.6
P, mg kg⁻¹	O	10	100.2 ± 5.0	26.0 ± 3.8	13.2 ± 0.6	14.7 ± 1.2	12.4 ± 0.8	17.4 ± 0.6	18.4 ± 0.8	59.5 ± 4.5	21.2 ± 1.3
	B	12	140.3 ± 10.0***	19.3 ± 2.7	14.3 ± 1.6	16.3 ± 2.4	13.4 ± 0.9	16.3 ± 0.5	19.2 ± 0.6	61.8 ± 1.4	18.6 ± 0.6
K, mg kg⁻¹	O	10	1159.9 ± 51.2	613.7 ± 38.4	430.6 ± 24.1	454.5 ± 21.9	494.4 ± 11.9	488.9 ± 6.8	403.1 ± 8.4	264.7 ± 16.5	229.2 ± 11.1
	B	12	1144.3 ± 79.0	445.6 ± 26.0***	401.8 ± 28.3	469.2 ± 36.3	491.6 ± 18.7	466.2 ± 5.5	383.5 ± 5.5	241.2 ± 4.7	222.2 ± 5.9
S, mg kg⁻¹	O	10	15.4 ± 1.5	19.6 ± 7.8	7.3 ± 2.7	4.6 ± 1.6	4.4 ± 1.1	2.7 ± 0.6	2.6 ± 0.3	3.1 ± 0.7	2.9 ± 0.5
	B	12	13.1 ± 1.0	7.0 ± 0.7***	4.4 ± 0.3	3.3 ± 0.4	3.4 ± 0.3	3.3 ± 0.5	3.5 ± 0.7	3.8 ± 0.4	2.8 ± 0.3
EC‡, dS m⁻¹	O	10	0.5 ± 0.05	0.9 ± 0.12	1.3 ± 0.10	1.3 ± 0.12	1.2 ± 0.10	0.7 ± 0.02	0.6 ± 0.03	0.5 ± 0.04	0.4 ± 0.01
	B	12	0.5 ± 0.02	0.6 ± 0.02***	0.7 ± 0.07***	0.8 ± 0.09***	0.7 ± 0.06***	0.6 ± 0.02	0.5 ± 0.03	0.4 ± 0.02	0.4 ± 0.01
H$_2$O, %	O	10	21.6 ± 0.5	24.6 ± 0.3	21.8 ± 0.6	22.9 ± 0.6	23.5 ± 0.3	20.6 ± 0.6	19.6 ± 1.1	18.1 ± 1.4	14.7 ± 0.8
	B	12	20.5 ± 0.9	23.4 ± 0.8	21.4 ± 0.5	21.3 ± 0.9	21.1 ± 1.0	21.0 ± 1.0	18.3 ± 1.7	18.3 ± 1.6	13.9 ± 1.1
pH	O	10	5.6 ± 0.07	5.4 ± 0.10	6.3 ± 0.09	7.0 ± 0.14	7.2 ± 0.10	7.6 ± 0.03	7.7 ± 0.04	7.7 ± 0.05	7.6 ± 0.03
	B	12	6.4 ± 0.11***	6.3 ± 0.05***	6.8 ± 0.11***	7.1 ± 0.14	7.5 ± 0.09	7.6 ± 0.04	7.7 ± 0.06	7.7 ± 0.03	7.6 ± 0.04

** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† O, on-row; B, between-row.
‡ Electrical conductivity.
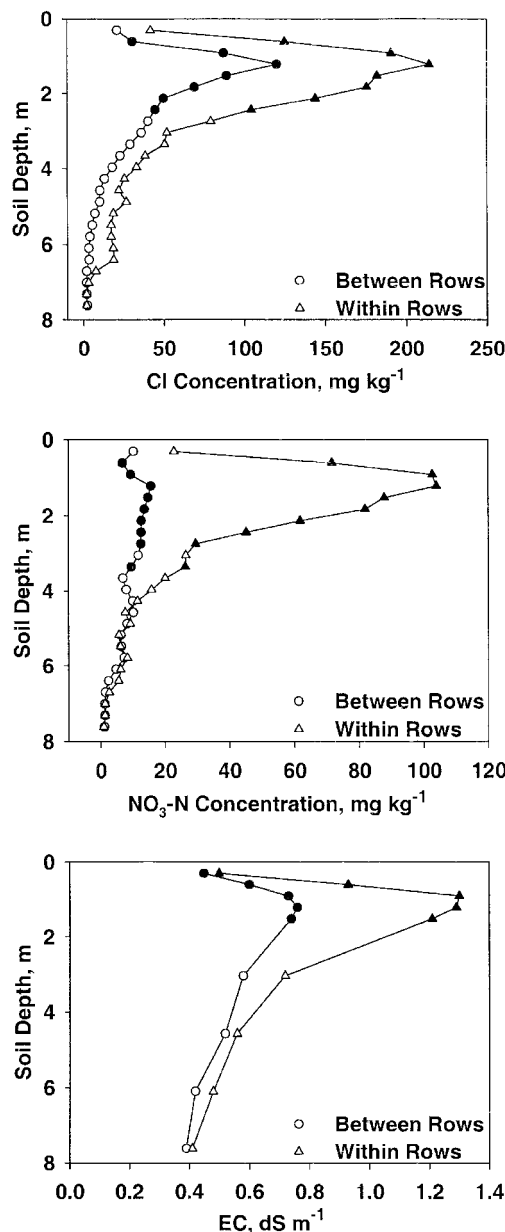
Fig. 3. Plots of constituents (1997 data) that show significant effect of "on-row" versus "between-row" locations at shallow depths (solid symbol indicates significant difference [$P < 0.05$]) but with trends toward little effect at increasing depths. (Adjusted northing = northing − 4 487 000; adjusted easting = easting − 570 000)

ferences with depth (Table 1). Soil bulk density was not measured and could have been a factor in differentially altering EC$_a$ due to compaction at the time of the compost operation. However, compacted soil would be expected to increase EC$_a$ resulting in higher values in the high-traffic areas between the rows. This was not observed at the known interrow location, indicating compaction was not a primary contributor to electrical conductivity differences. Additionally, compaction effects are generally not alleviated over short time periods (Brevik et al., 2002; Kay et al., 1985, Orr, 1975) so the dynamics observed at this site (discussed later) probably are due to the movement of ions over time.

Table 2. Correlations of the EM-38 instrument readings (V38, vertical orientation; H38, horizontal orientation) with soil properties by depth. Pearson correlation coefficients are shown with indication of significance to a depth of 3.0 m.

	Depth (m)											
	0.3		0.6		0.9		1.2		1.5		3.0	
Property	V38	H38	V38	H38	V38	H38	V38	H38	V38	H38	V38	H38
pH	−0.79***	−0.71***	−0.80***	−0.74***	−0.57**	−0.58**	–	–	–	–	–	–
EC†	–	–	0.46*	0.71***	0.73***	0.84***	0.64**	0.74***	0.72***	0.74***	0.64**	0.66***
NO_3–N	–	0.58**	0.60**	0.80***	0.85***	0.90***	0.76***	0.79***	0.79***	0.77***	0.49*	–
NH_4	–	–	–	–	–	–	−0.58**	−0.53*	–	–	–	–
P	−0.62**	−0.56**	–	–	–	–	–	–	–	–	–	–
S	0.49*	–	–	0.43*	0.49*	–	–	–	–	–	–	–
Cl	–	0.55**	–	0.6**	–	0.56**	–	0.46*	0.51*	0.58**	–	–
K	–	–	0.63**	0.65**	–	–	–	–	–	–	0.44*	0.53*
H_2O	–	–	–	–	–	–	–	–	–	–	–	–

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Electrical conductivity.

Site I Electromagnetic Induction readings

Correlations of EMI instrument readings (taken at individual coring sites at ground level) with soil constituents are shown in Table 2 for the EM-38 operated in the vertical and horizontal dipole mode. Table 2 displays significant correlations for each instrument–constituent combination to depths of 3.0 m. The strong associations of the EMI readings with NO_3–N, Cl, EC, and pH indicate the instrument was responding to ionic content patterns in the soil. The EMI–constituent patterns are associated with known row locations and provide ancillary support for the use of EMI in identifying subsurface features such as those associated with this former waste management site.
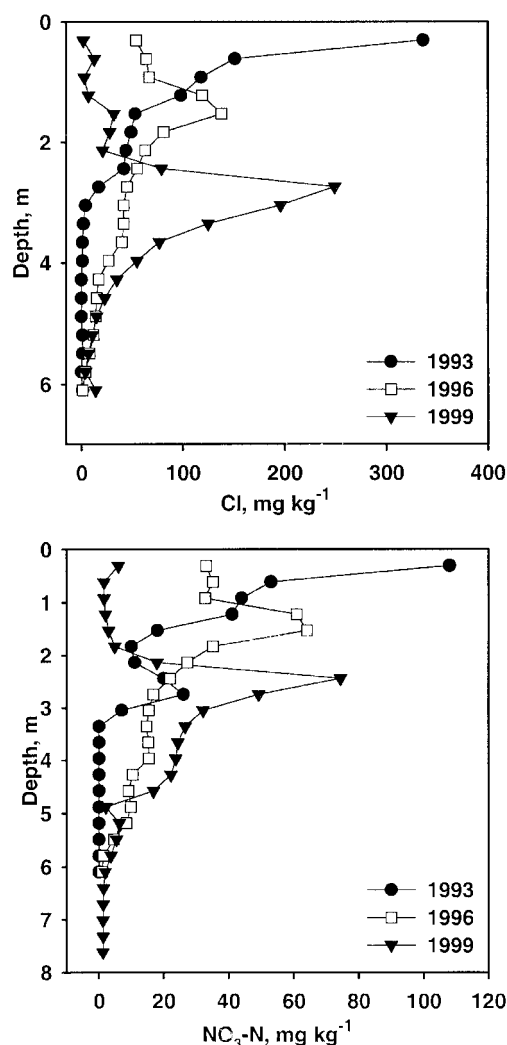
Site II

Site II, located approximately 36 m north of Site I, demonstrated the movement of nutrients beneath a compost row location. Soil cores were taken every three years beginning in 1993 while the compost site was in operation. In 1993 the highest concentrations of Cl and NO_3–N were close to the surface (Fig. 4). By 1996 the highest concentration of both Cl and NO_3–N occurred at a depth of about 1.5 m. The soil cores taken in 1999 indicate movement of both Cl and NO_3–N to approximately 3 m. Movement of Cl and NO_3–N occurred at an approximate rate of 0.5 m per year at this site over the six-year period.

Difference Maps

The designated subsection, Site I, was surveyed on 1.5-m transects in 1997 using the EM-38 and the global positioning system generating the image displayed in Fig. 5 (top graph). Similar EMI surveys were conducted in both 1998 and 1999, with the images displayed in Fig. 5 (middle and bottom graphs). A comparison of the images reveals temporal changes over the period of these surveys. The first map from 1997 clearly distinguishes row locations; by 1998 the locations appear less distinct, with the 1999 image showing very little of the original delineation. An overall decrease in EC_a is consistent with the leaching of nutrients observed at Site II. At Site II, by 1999 much of the Cl and NO_3–N had moved beyond the range of detection of the EM-38

(Fig. 4), which would result in a map with diminished features and lower as seen in the 1999 map (Fig. 5, bottom).

The temporal differences are enhanced by considering grid difference maps. Images generated by subtracting the 1997 grid map from the 1998 (top graph)

Fig. 4. Soil core data for cores taken in 1993, 1996, and 1999 showing Cl and NO_3–N concentrations with depth at Site II (Fig. 1).
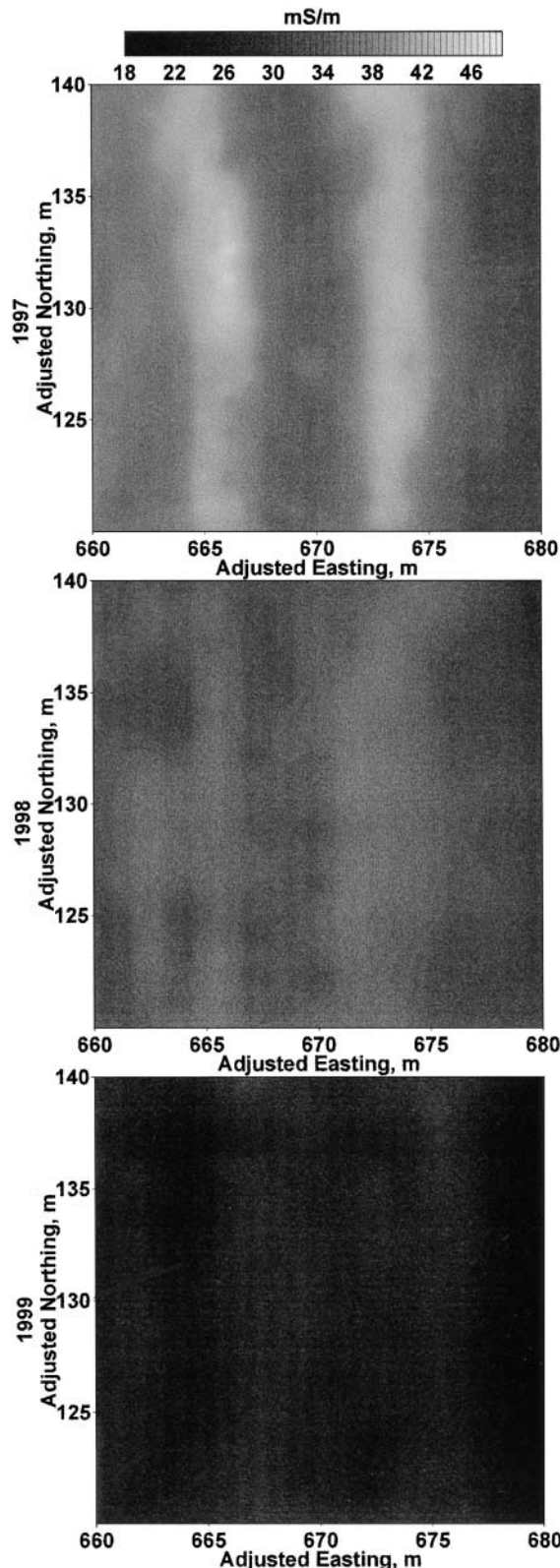
Fig. 5. Apparent soil electrical conductivity (EC$_a$) maps obtained using 1997 (top graph), 1998 (middle), and 1999 (bottom) data, based on EM38 operated in the horizontal mode. Note that by 1999 little EC$_a$ delineation of rows is evident.
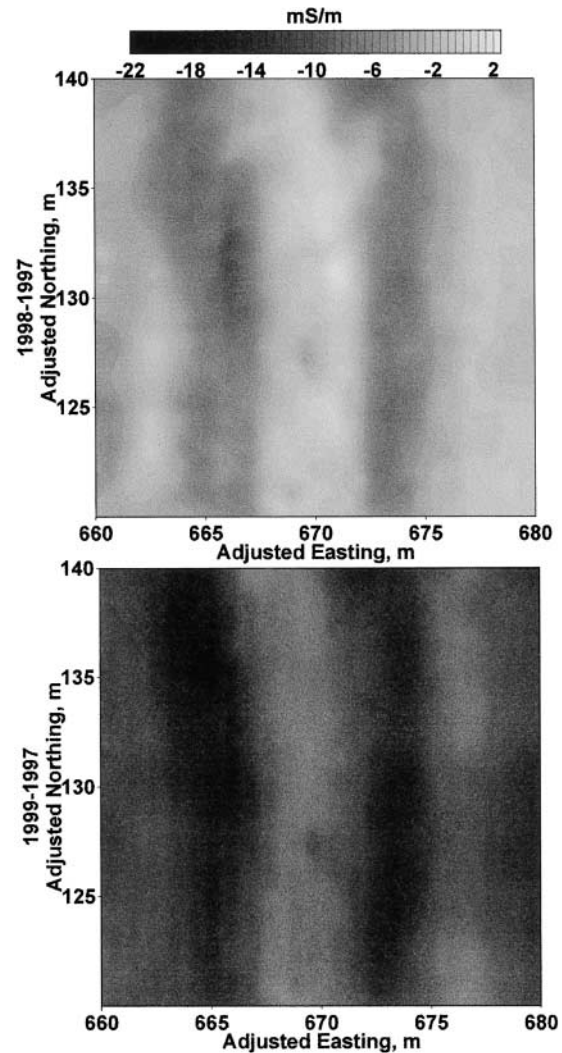

Fig. 6. Map differences obtained by subtracting 1997 reference apparent soil electrical conductivity (EC$_a$) grid data from 1998 (top graph) and 1999 EC$_a$ grid data (bottom). Darker areas show relative decrease in EC$_a$ suggesting mechanical movement of the nutrients, as well as biological relocation.

and 1999 (bottom) grid maps are shown in Fig. 6. The decrease in EC$_a$ as depicted by the darker areas is clear, as well as the slight elevation in EC$_a$ between the rows (Fig. 6). The increasing EC$_a$ between the rows, as well as the diminished EC$_a$ within the row, suggests biological relocation, as well as mechanical movement of dissolved salts. Additionally, some of the observed temporal changes may be due to differential uptake of nutrients by vegetation with the areas of higher concentrations also being the areas of greater nutrient uptake. Diminished EC$_a$ beneath the row with poorly defined row boundaries may indicate some lateral diffusion of salts as well.

CONCLUSIONS

Electromagnetic induction measurements and EC$_a$ maps were demonstrated to have value in locating areas of high nutrient buildup associated with a composting site that was active from 1991 to 1994, up to four years after the composting was discontinued. When a EC$_a$ map was used in conjunction with known row locations for locating an intensive soil core sampling program,

the resulting core constituent values differentiated ($P <$ 0.05) the center of the compost rows and the region between the rows for NO_3–N, Cl, and EC to a depth of 1.5 m. Also, EMI readings correlated ($P < 0.05$) to NO_3–N, Cl, and EC to a depth of 1.5 m providing ancillary support of using EMI to identify subsurface features such as those associated with this former waste management site. Additionally, sequential EC_a maps of the former compost site demonstrated the dynamics of a field with respect to soil EC. The temporal changes can be enhanced by image processing, highlighting EC_a changes occurring from year to year. Time sequence maps provided visual insights into temporal soil dynamics revealing changes in EC_a due to leaching of dissolved salts and possible plant nutrient uptake, as well as diffusion of nutrients within the surveyed site. The use of EC_a maps coupled with image processing methods and soil cores can be useful in assessing abandoned manure management sites for nutrient buildup up to four years after abandonment.

REFERENCES

Brevik, E., T. Fenton, and L. Moran. 2002. Effect of soil compaction on organic carbon amounts and distribution, south-central Iowa. Environ. Pollut. 116:S137–S141.

Corwin, D.L., and J.D. Rhoades. 1982. An improved technique for determining soil electrical conductivity–depth relations from above-ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46:517–520.

Doran, J.W., A. Kessavalou, G.L. Hutchinson, M.F. Vigil, and A.D. Halvorson. 1996. Influence of cropping/tillage management on soil fertility and quality of former CRP land in the central high plains. p. 205–211. In J.L. Havlin (ed.) Great Plains Soil Fertility Conf., Denver, CO. 5–6 Mar. 1996. Vol. 6. Kansas State Univ., Manhattan, KS.

Eigenberg, R.A., J.W. Doran, J.A. Nienaber, R.B. Ferguson, and B.L. Woodbury. 2001. Electrical conductivity monitoring of soil condition and available N with animal manure and a cover crop. Agric. Ecosyst. Environ. 1834:1–11.

Eigenberg, R.A., J.W. Doran, J.A. Nienaber, and B.L. Woodbury. 2000. Soil conductivity maps for monitoring temporal changes in an agronomic field. p. 249–265. In J.A. Moore (ed.) Animal, Agricultural and Food Processing Wastes. Proc. Int. Symp., 8th, Des Moines, IA. 9–11 Oct. 2002. Am. Soc. of Agric. Eng., St. Joseph, MI.

Eigenberg, R.A., R.L. Korthals, and J.A. Nienaber. 1998. Geophysical electromagnetic survey methods applied to agricultural waste sites. J. Environ. Qual. 27:215–219.

Gilbertson, C.B., J.R. Ellis, J.A. Nienaber, T.M. McCalla, and T.J. Klopfenstein. 1975. Properties of manure accumulations from midwest beef cattle feedlots. Trans. ASAE 18:327–330.

Golden Software. 1995. Surfer for Windows user guide. Golden Software, Golden, CO.

Kay, B.D., C.D. Grant, and P.H. Groenevelt. 1985. Significance of ground freezing on soil bulk density under zero tillage. Soil Sci. Soc. Am. J. 49:973–978.

McNeill, J.D. 1990. Use of electromagnetic methods for groundwater studies. p. 191–218. In S.H. Ward (ed.) Investigations in geophysics. No. 5. Geotechnical and environmental geophysics. Soc. of Exploration Geophysicists, Tulsa, OK.

Orr, H.K. 1975. Recovery from soil compaction on bluegrass range in the Black Hills. Trans. ASAE 18:1076–1081.

Ranjan, R.S., T. Karthigesu, and N.R. Bulley. 1995. Evaluation of an electromagnetic method for detecting lateral seepage around manure storage lagoons. ASAE Paper no. 952440. Am. Soc. of Agric. Eng., St. Joseph, MI.

SAS Institute. 1986. SAS user's guide: Statistics. SAS Inst., Cary, NC.

Smith, J.L., and J.W. Doran. 1996. Measurement and use of pH and electrical conductivity for soil quality analysis. p. 169–185. In J.W. Doran and A.J. Jones (ed.) Methods of assessing soil quality. SSSA Spec. Publ. 49. SSSA, Madison, WI.

Sudduth, K.A., and N.R. Kitchen. 1993. Electromagnetic induction sensing of claypan depth. ASAE Paper no. 931531. Am. Soc. of Agric. Eng., St. Joseph, MI.

Williams, B.G., and G.C. Baker. 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Aust. J. Soil Res. 20:107–118.